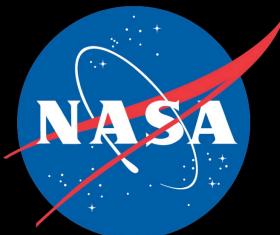




# Observations and characterization of binary near-Earth asteroid 65803 Didymos, the target of the AIDA mission

S. P. Naidu, L. A. M. Benner, M. Brozovic, J. D. Giorgini, S. J. Ostro, M.  
C. Nolan, J. L. Margot, P. Pravec, P. Scheirich, D. J. Scheeres

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# Part 1: Physical characterization of Didymos

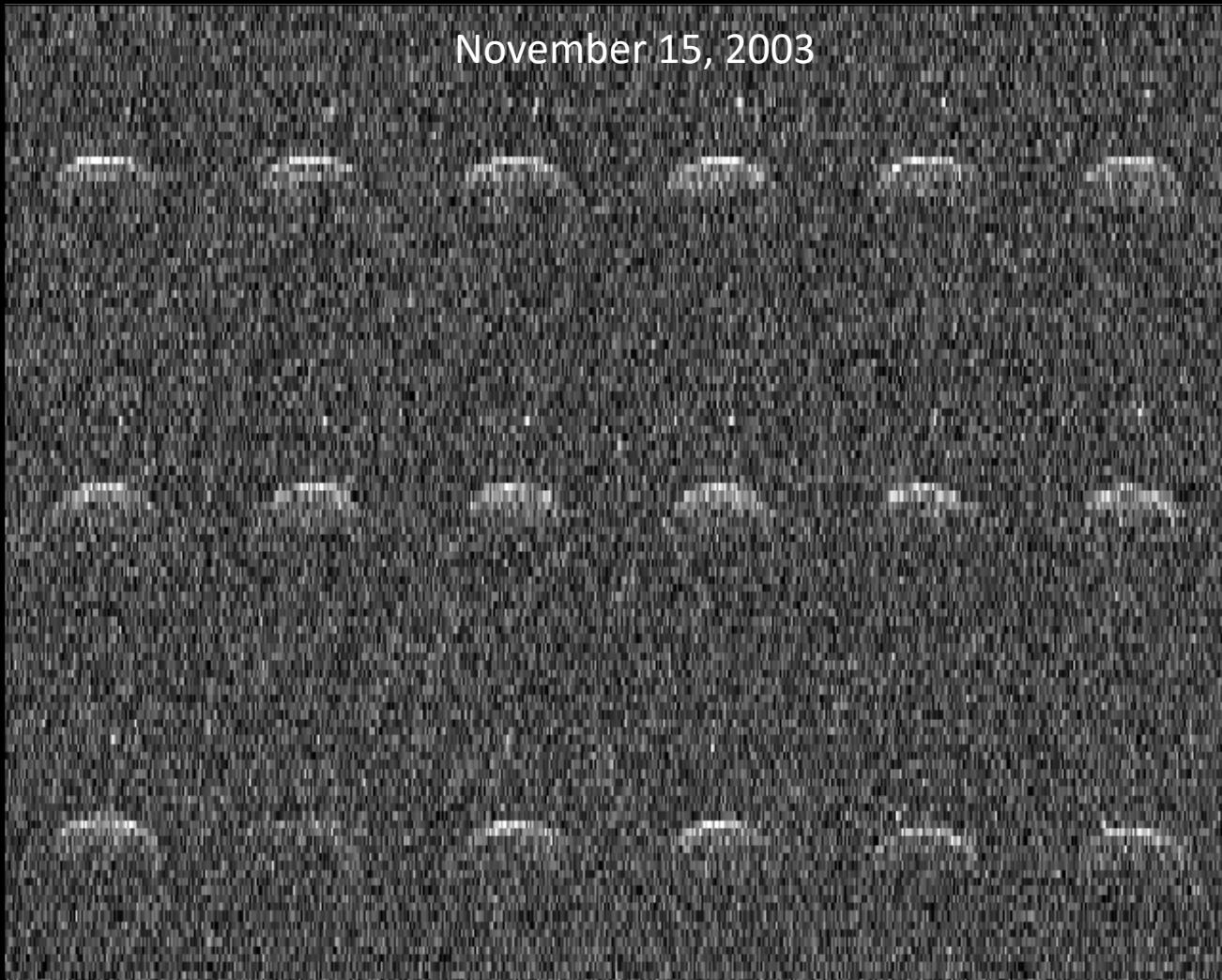
# Data

- 2003 radar observations
  - Goldstone on Nov 14, 15 (range resolution 75 m/pixel, sub-radar latitude -30 degrees)
  - Arecibo on Nov 23, 24, 26 (range resolution 15m/pixel, sub-radar latitude -7 to -12 degrees)
- 2003 lightcurve observations (Pravec et al. 2006)
  - Nov 20-24, Nov 26- Dec 04, Dec 16-20 (sub-radar latitudes < +9 degrees)

# Goldstone images

November 15, 2003

Range (75 m/pixel) →



Doppler Frequency (0.5 Hz/pixel) →

# Arecibo images

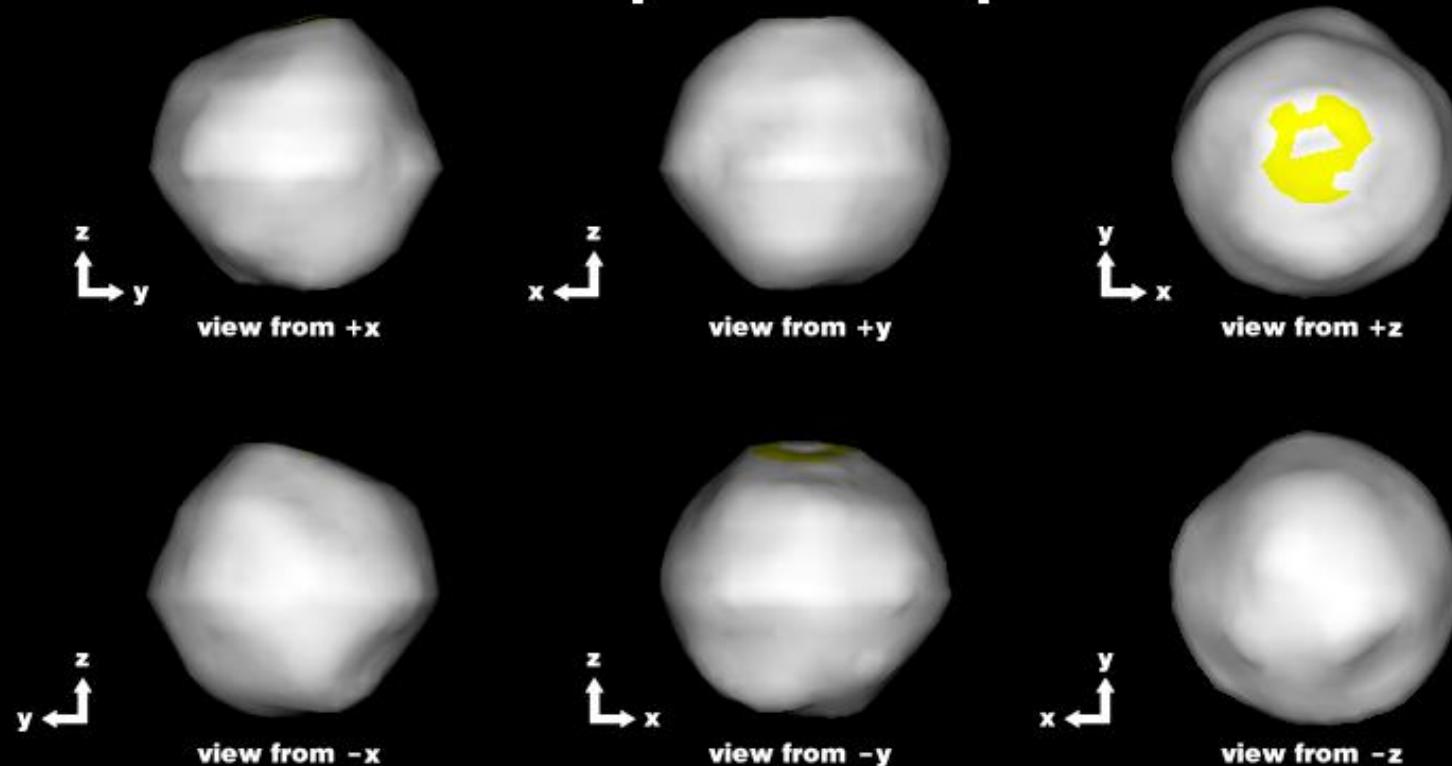
November 24, 2003

Range (15 m/pixel) →

Doppler frequency (0.3 Hz/pixel) →

# Primary shape

1 km



Dimensions: 797 m x 783 m x 761 m (Uncertainty is 10%  
in x, y and 15% in z dimension)

Volume equivalent diameter: 780 m (+/- 12%)

Model facets: 1996

Model resolution: 50 m

# Secondary

Arecibo images

Nov 23, 2003  
(47 runs)

Simple stacking

Shift & stack

# Secondary

Nov 23



47 runs

Resolution: 15 m x 0.0375 Hz

Nov 24



54 runs

Resolution: 15 m x 0.0375 Hz

# Secondary

Nov 23

R=60-90 m  
P=9-12 h

Nov 24



47 runs

Resolution: 15 m x 0.0375 Hz



54 runs

Resolution: 15 m x 0.0375 Hz

# Secondary shape

Nov 23 (Arecibo images)



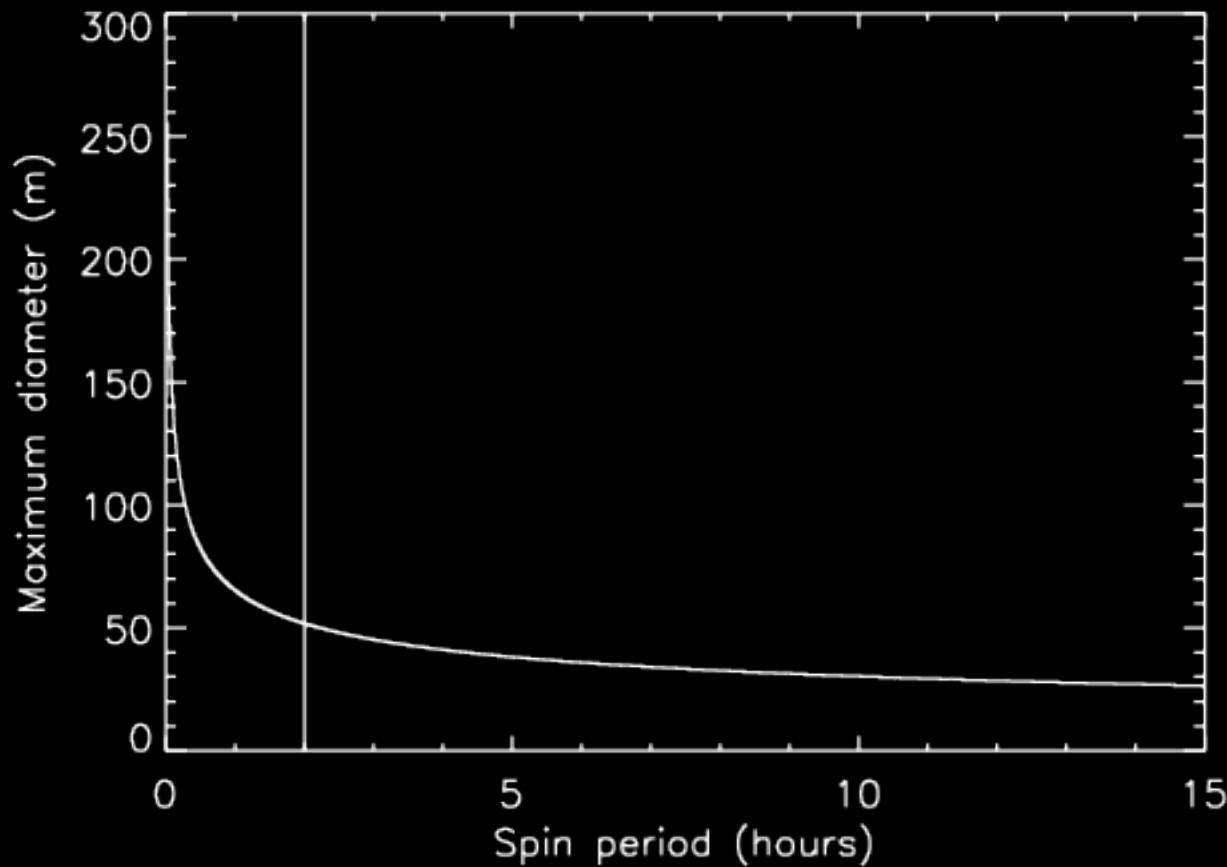
Nov 24 (Arecibo images)



Image resolutions: 15 m x 0.0375 Hz

Each image is integrated over 15 degrees of rotation.

# $3\sigma$ limits on tertiary



If  $P > 2$  hours,  $D < 50$  meters.

# Mutual orbit

- Data: 108 delay and Doppler measurements from Arecibo and Goldstone images and spectra.
  - Primary COM was modeled using the shape model.
  - Secondary COM was assumed to be 75 m behind leading edge.
- Explored initial conditions around solution in Scheirich & Pravec (2009)
- Fit values:  $a = 1188$  m,  $e < 0.045$ ,  $P = 11.92$  hours,  $M = 5.377 \times 10^{11}$  kg (+/- 10%), density =  $2164 \text{ kg/m}^3$  (+/- 30%)
  - Consistent with values derived from Scheirich & Pravec (2009).
  - Spin pole < 2 degrees away from Scheirich & Pravec (2009)

# Part 1: Summary

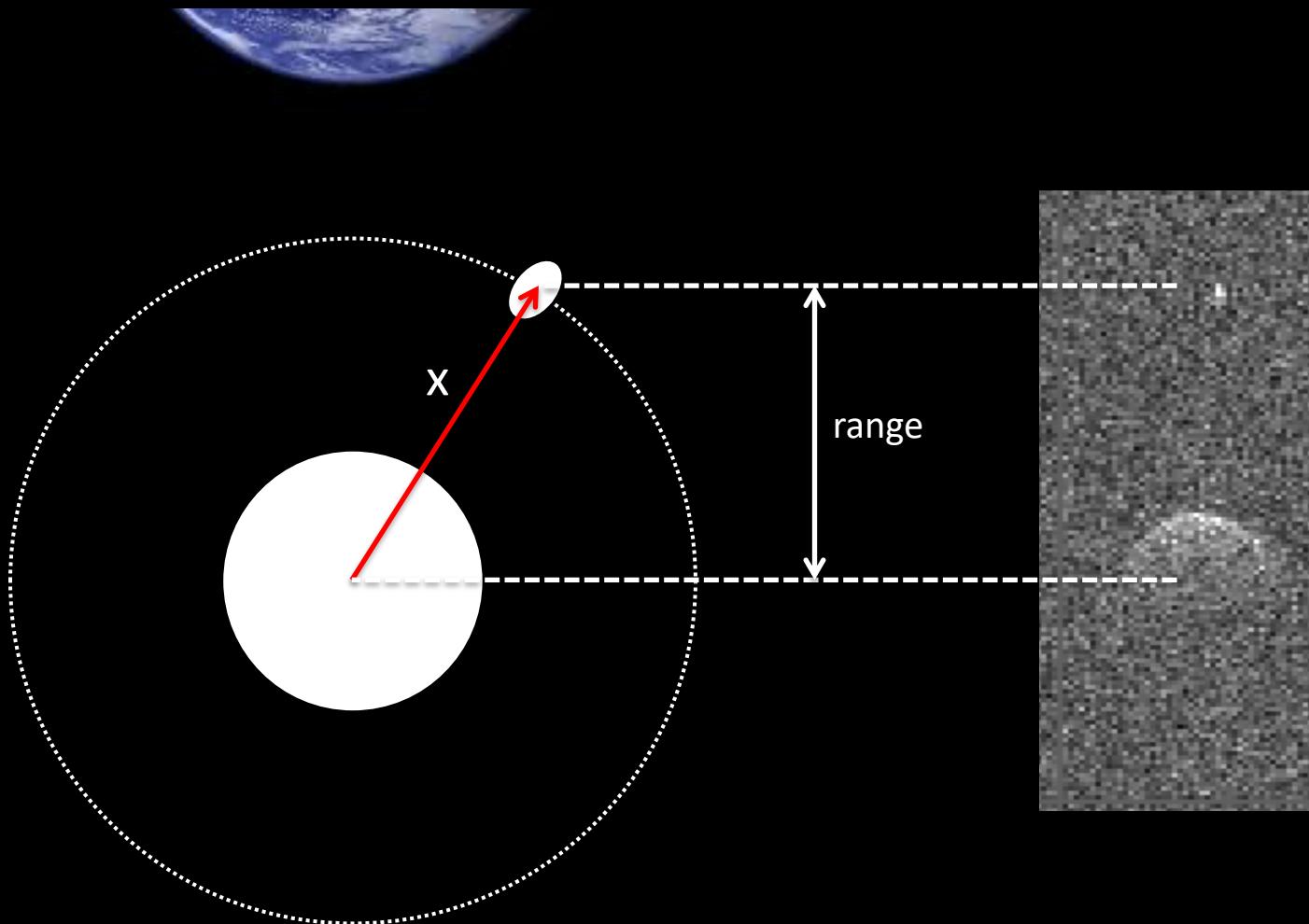
- Primary shape and dimensions (797 m x 783 m x 761 m: Uncertainties +/- 10% in x, y and +/-15% in z)
- Secondary shape is not round. It's diameter is between 120 and 180 m and spin is most likely synchronous.
- Any potential tertiary would most likely be smaller than 50 m in diameters unless it is spinning faster than 2 hours.
- Radar derived mutual orbit is consistent with that obtained by Scheirich and Pravec (2009).

# Part 2: Using Ground-based Radar to Detect Changes in the Didymos Binary Orbit Due to DART Impact

# Estimating signal-to-noise ratios in 2022

- We used the size, spin period, and the radar albedo derived from 2003 for estimating the SNRs in 2022.
- Close approach distance in 2022 will be about 1.5 times that in 2003.
  - Setups identical to those used in 2003 will yield 1/6<sup>th</sup> the SNRs.
  - We can boost the signal/pixel by compromising on resolution.
- At Arecibo, we should be able to obtain delay-Doppler images and echo power spectra.
- Goldstone should be able to obtain echo power spectra but if we use Green Bank to receive, we will most likely be able to obtain images as well.
- Finest images will most likely have resolutions of 75 m, which should allow us to see the primary as well as the secondary.

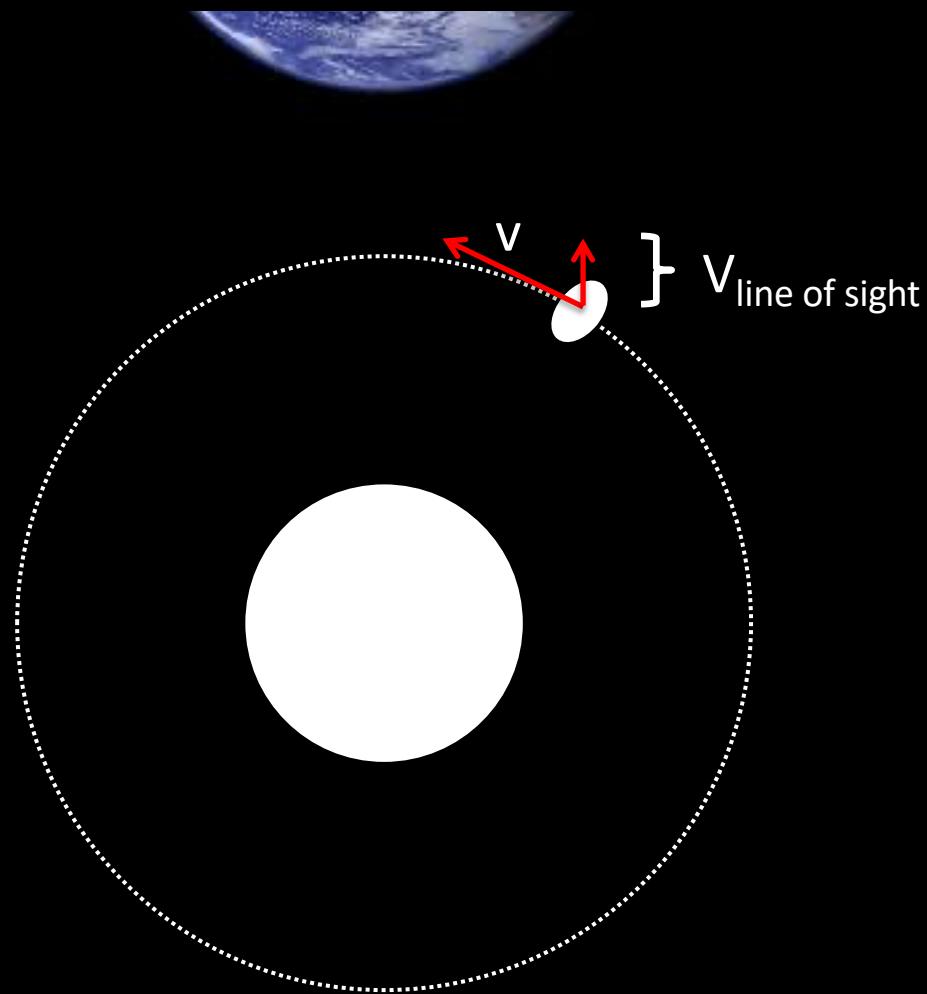
# Radar observables (range)



Pole-on view of a binary system

Radar delay-Doppler image

# Radar observables (Doppler)

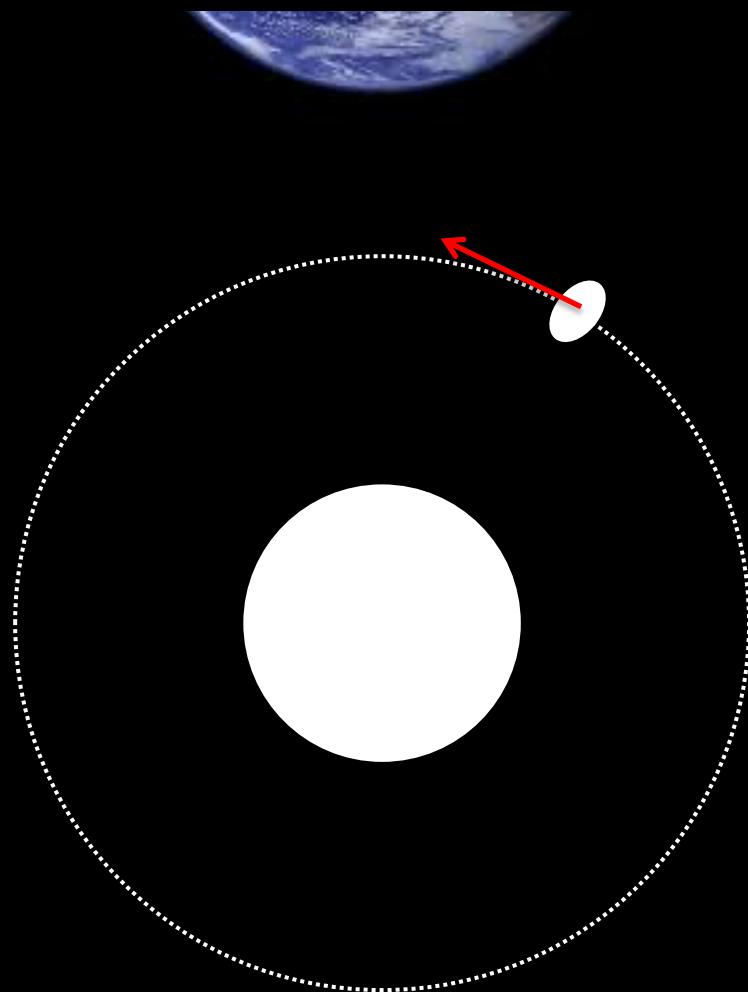


Pole-on view of a binary system

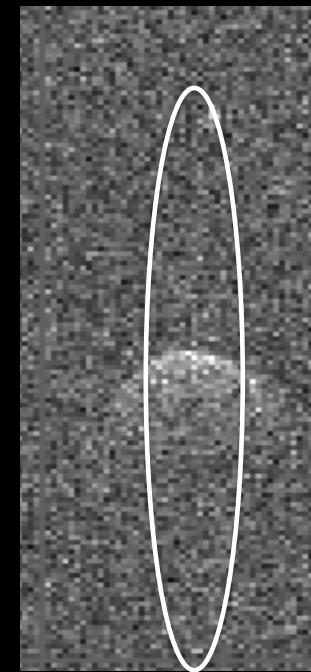


Radar delay-Doppler image

# Radar observables (Doppler)



Pole-on view of a binary system



Radar delay-Doppler image

# Predicted SNRs at Goldstone and Green Bank for the satellite

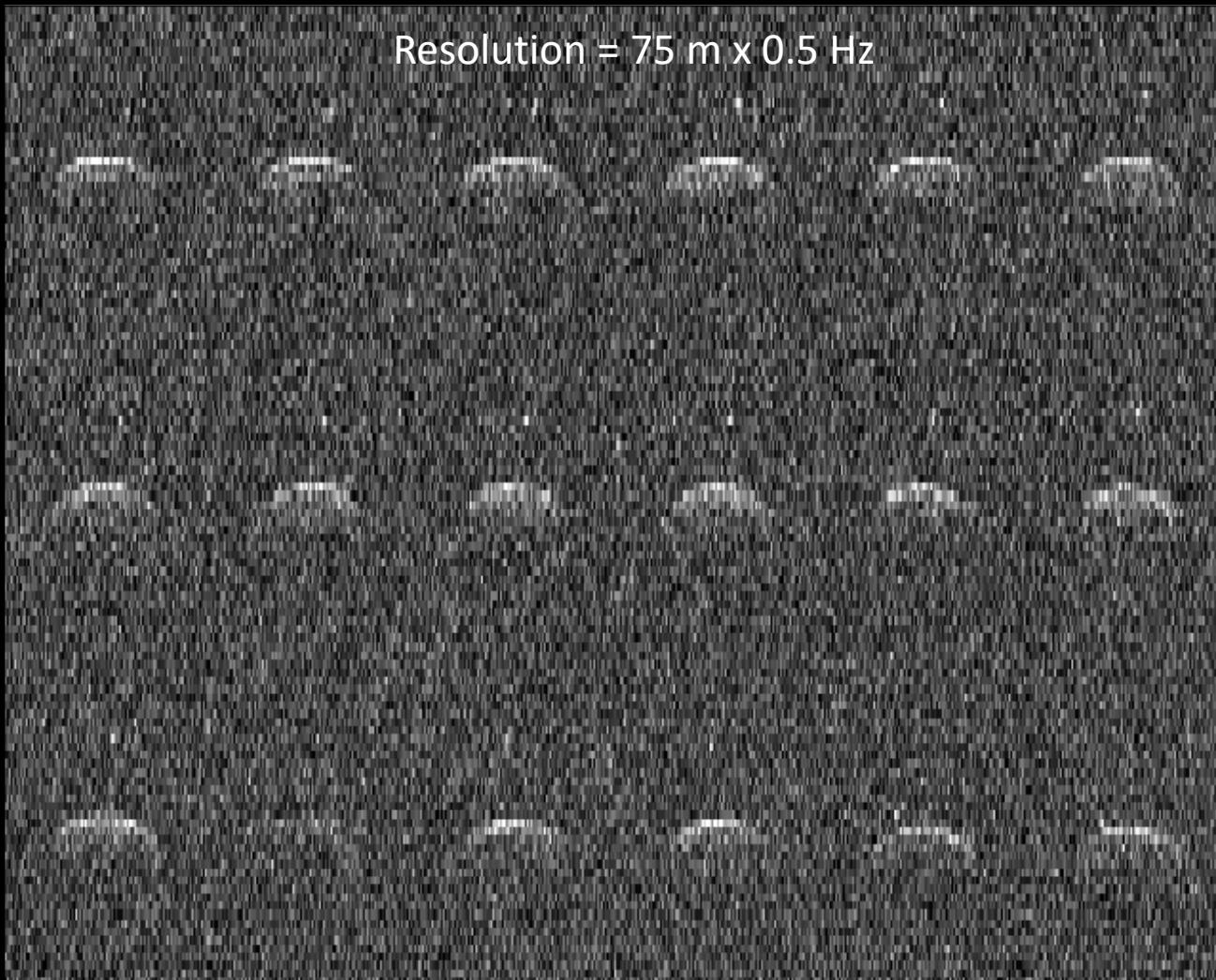
UTC date	dist (au)	Dec. (deg)	SNR/ day	SNR/ run	SNR/ (DSS-14 → Green Bank)
2022 Sep 25	0.078	-34	6	1	
2022 Sep 26	0.076	-34	9	1	
2022 Sep 27	0.075	-33	11	2	
2022 Sep 28	0.074	-32	12	2	
2022 Sep 29	0.073	-32	14	2	
2022 Sep 30	0.072	-31	16	2	
2022 Oct 01	0.072	-30	18	2	5
2022 Oct 02	0.072	-28	19	2	5
2022 Oct 03	0.071	-27	20	2	5
2022 Oct 04	0.071	-26	21	2	5
2022 Oct 05	0.071	-25	22	2	5
2022 Oct 06	0.072	-23	23	2	5
2022 Oct 07	0.072	-22	23	2	5
.					
2022 Oct 14	0.078	-12	19	2	5
2022 Oct 15	0.080	-11	18	2	5
.					
2022 Oct 21	0.090	-4	12	1	2
2022 Oct 22	0.092	-3	11	1	2
2022 Oct 23	0.094	-2	10	1	2
2022 Oct 24	0.095	-1	9	1	2

# Predicted Arecibo SNRs for the satellite

UTC date	dist (au)	Dec. (deg)	SNR/ day	SNR/ run
2022 Oct 24	0.095	-1	44	13
2022 Oct 25	0.097	0	55	13
2022 Oct 26	0.099	+1	61	14
2022 Oct 27	0.101	+2	64	14
2022 Oct 28	0.103	+3	65	14
2022 Oct 29	0.105	+4	65	13
2022 Oct 30	0.107	+4	63	12
2022 Oct 31	0.110	+5	60	12
2022 Nov 01	0.112	+6	58	11
2022 Nov 02	0.114	+7	55	10
2022 Nov 03	0.116	+7	52	9
2022 Nov 04	0.118	+8	49	9
2022 Nov 05	0.120	+9	46	8
2022 Nov 06	0.122	+9	44	8
2022 Nov 07	0.125	+10	41	7
2022 Nov 08	0.127	+10	39	7
.				
2022 Dec 04	0.181	+22	10	2
2022 Dec 05	0.183	+22	10	2
2022 Dec 06	0.185	+22	9	2

# Goldstone Images from 2003 Nov 15

Range (75 m/pixel) →



Doppler Frequency (0.5 Hz/pixel) →

The highest Arecibo SNRs in 2022 will be 1.6x stronger than in these images.  
The highest Goldstone → Green Bank SNRs will be about half of these.

# Arecibo Images from 2003 Nov 24

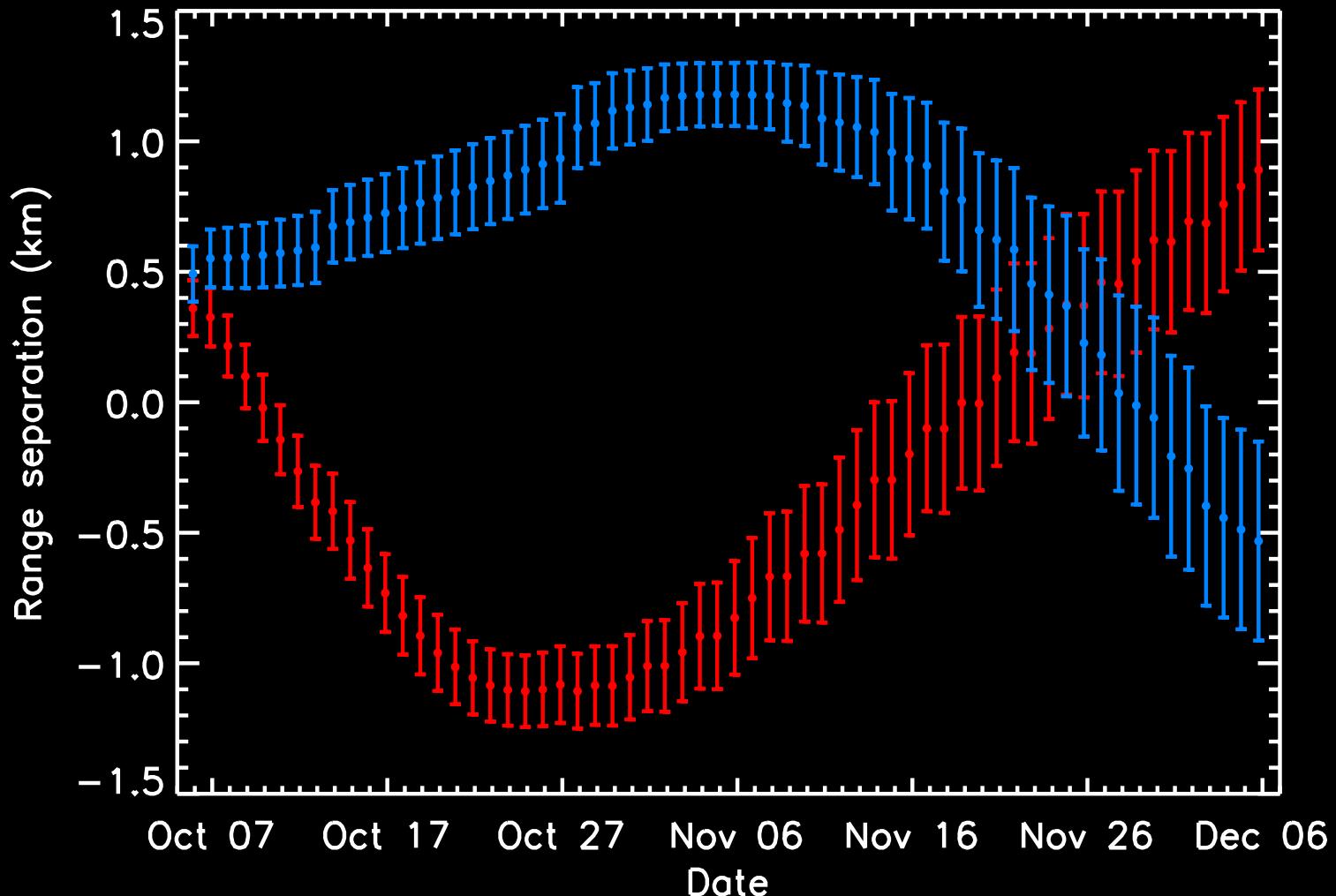


The strongest Arecibo SNRs in 2022 will be 1/6th of those shown here

# Assumptions for range and Doppler displacement predictions

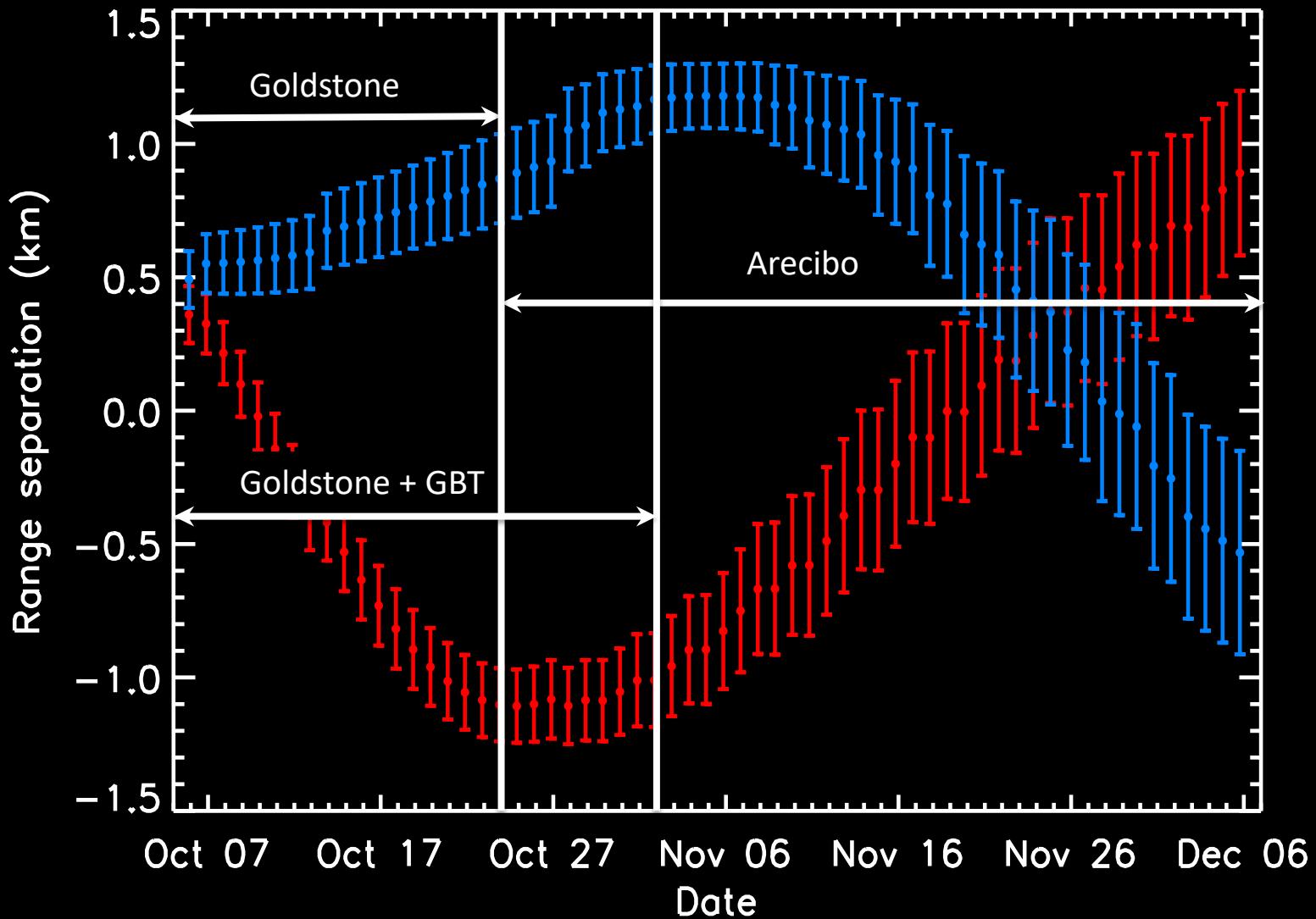
- An orbital period change of 7 minutes due to the DART impact.
- The orbit pole uncertainty of 10 degrees.
- The orbital period uncertainty of 0.004 hours.
- The orbital position uncertainty of 5 degrees on the day of the impact.
- Measurement errors in Doppler and range separations of +/- 1 Hz and +/- 100 m.

# Range displacement predictions

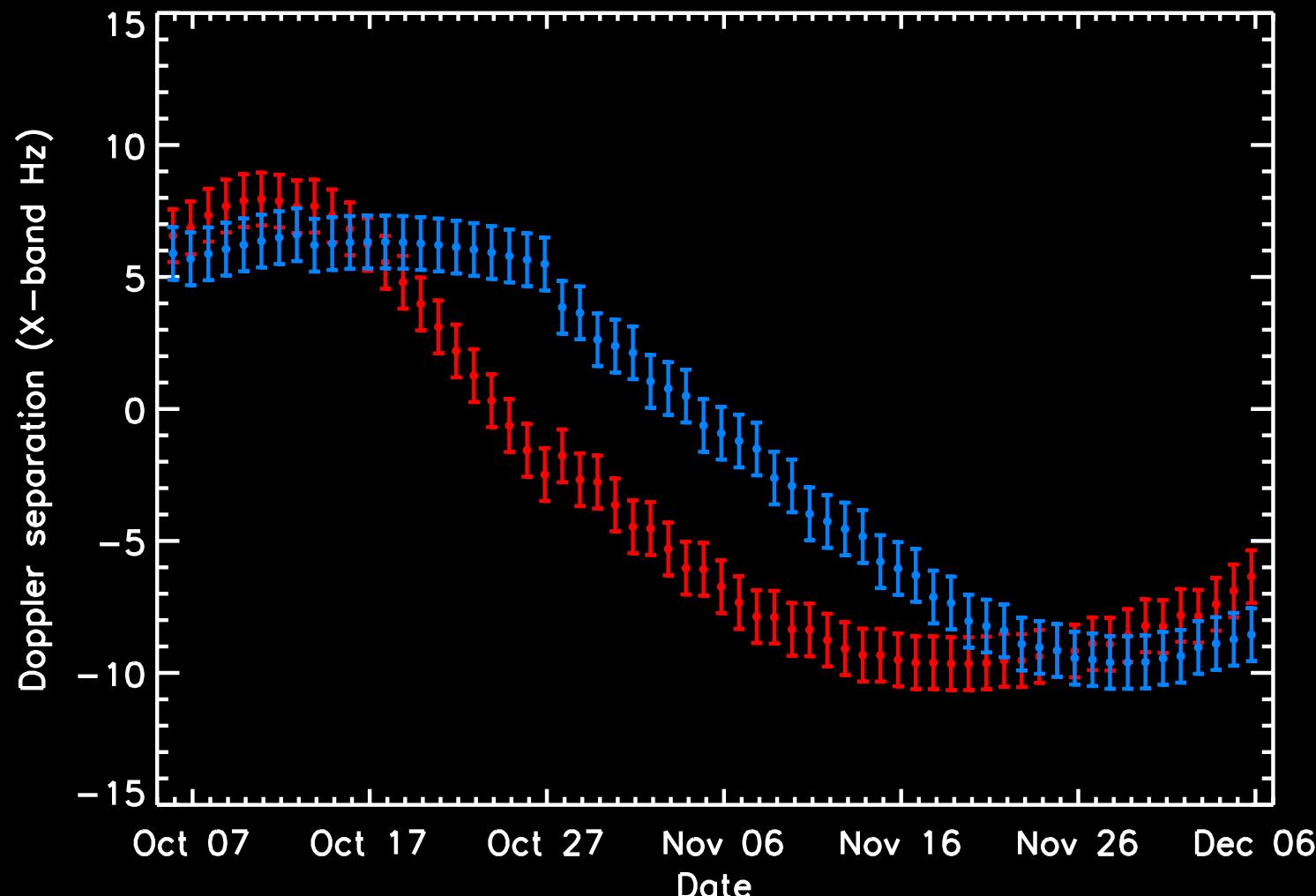


Red and blue points indicate modeled range separation measurements for the **unperturbed** and **perturbed** orbits respectively. Error bars include orbital and measurement uncertainties

# Range displacement predictions

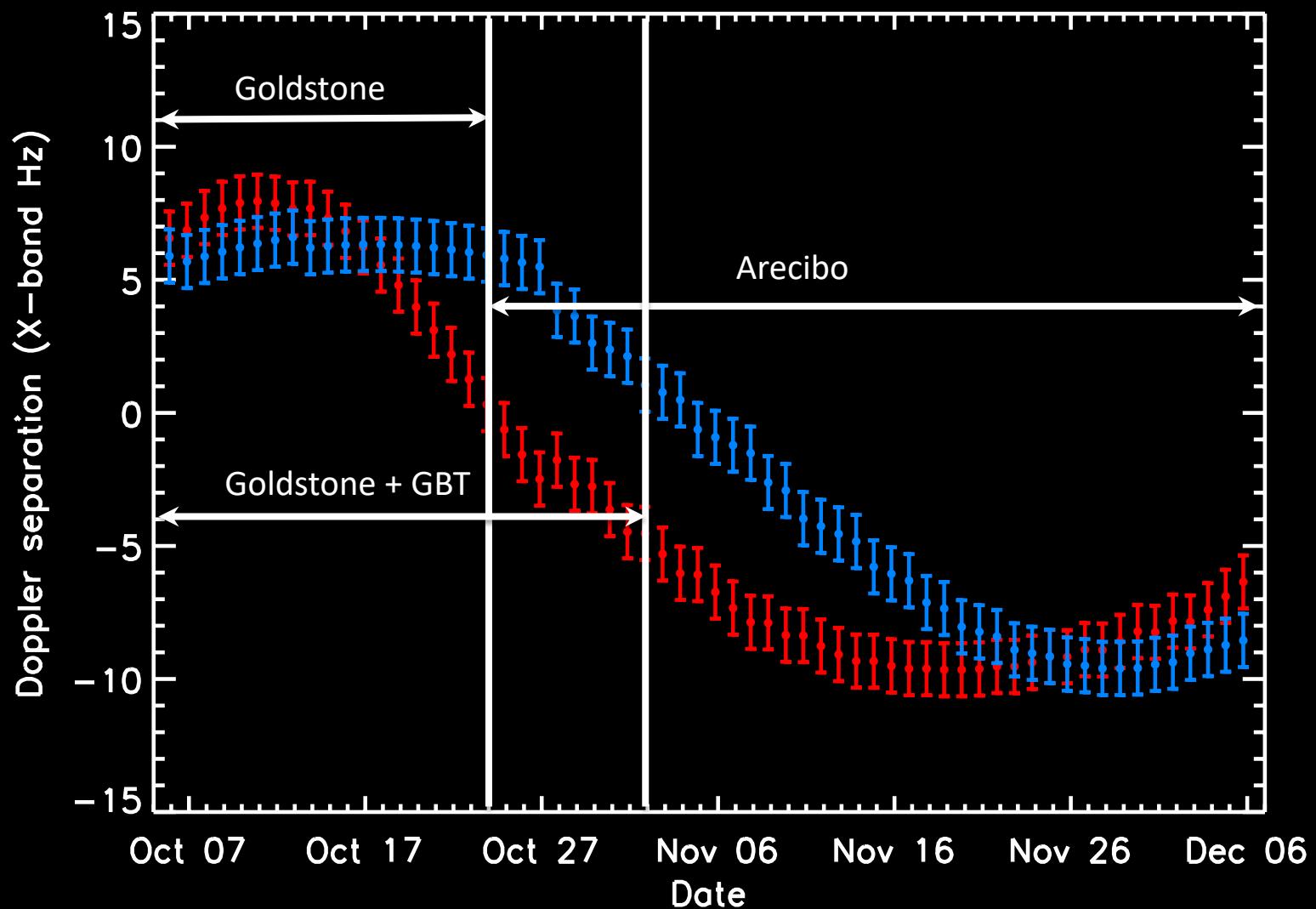


# Doppler displacement predictions



Red and blue points indicate modeled Doppler separation measurements for the **unperturbed** and **perturbed** orbits respectively. Error bars include orbital and measurement uncertainties

# Doppler displacement predictions



# Part 2: Conclusions

- Arecibo signal-to-noise ratios in 2022 will be a factor of six lower than in 2003 but still strong enough for imaging.
  - Arecibo SNRs will still be about 60% higher than SNRs at Goldstone in 2003.
- The secondary will be detectable at Arecibo in delay-Doppler for about 2 weeks (Oct 24 to Nov 06) with SNRs comparable to those at Goldstone in 2003.
- Goldstone SNRs will be 1/4<sup>th</sup> of the values in 2003.
- If we transmit at Goldstone and receive at Green Bank, SNRs increase by 2.3 and the detectability of the satellite lengthens by about one week.
- Detection of the secondary in delay-Doppler images using Goldstone and Green Bank is likely for about 1 week before and after the planned DART impact date of Oct 5.
  - The predicted 7 minute orbit change should be detectable at Goldstone/Green Bank even in echo power spectra.

# Predicted Goldstone SNRs for 2001 CB21

UTC date	dist (au)	Dec. (deg)	SNR/ day	SNR/ run
2022 FEB 24	0.062	28	80	4
2022 FEB 25	0.056	28	120	6
2022 FEB 26	0.050	28	180	9
2022 FEB 27	0.045	28	270	13
2022 FEB 28	0.041	27	410	18
2022 MAR 01	0.037	25	600	25
2022 MAR 02	0.034	23	800	33
2022 MAR 03	0.033	19	930	38
2022 MAR 04	0.032	14	930	39
2022 MAR 05	0.033	9	810	35
2022 MAR 06	0.036	4	610	28
2022 MAR 07	0.039	0	410	20
2022 MAR 08	0.044	-3	270	14
2022 MAR 09	0.049	-5	170	10
2022 MAR 10	0.054	-7	110	7
2022 MAR 11	0.060	-9	70	5

Assumptions: D = 650 m, P=2.1 hours

# Predicted Arecibo SNRs for 2001 CB21

UTC date	dist (au)	Dec. (deg)	SNR/ day	SNR/ run
2022 FEB 08	0.171	24	20	4
2022 FEB 09	0.164	24	24	4
2022 FEB 10	0.157	25	28	5
.				
2022 FEB 24	0.063	28	970	110
2022 FEB 25	0.058	28	1440	160
2022 FEB 26	0.052	28	2120	230
2022 FEB 27	0.047	28	3220	330
2022 FEB 28	0.042	27	5070	470
2022 MAR 01	0.038	26	7650	660
2022 MAR 02	0.035	24	10840	890
2022 MAR 03	0.033	20	13470	1070
2022 MAR 04	0.032	15	14190	1120
2022 MAR 05	0.033	10	12300	1020
2022 MAR 06	0.036	5	8540	810
2022 MAR 07	0.039	1	4930	590

Assumptions: D = 650 m, P=2.1 hours

# BACKUP

# Goldstone Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (1/2)

start date	Start	Stop	Monostatic								
			UTC			SNR/			SNR/ GSSR/GBT		
			RA	dec	dist	lat	runs	day	run	Overlap	
			(degrees)	(au)	(deg)						
2022 Sep 25	10:07	-11:08	47	-34	0.078	-50	23	33	7		
2022 Sep 26	09:58	-11:33	50	-34	0.076	-50	37	45	8		
2022 Sep 27	09:52	-11:56	53	-33	0.075	-50	49	56	8		
2022 Sep 28	09:47	-12:17	56	-32	0.074	-50	60	66	9		
2022 Sep 29	09:43	-12:38	59	-32	0.073	-49	71	75	9		
2022 Sep 30	09:39	-12:58	62	-31	0.072	-49	82	85	10		
2022 Oct 01	09:35	-13:17	65	-30	0.072	-48	92	93	10	09:35-10:07	
2022 Oct 02	09:32	-13:36	67	-28	0.072	-47	102	100	10	09:32-10:32	
2022 Oct 03	09:29	-13:54	70	-27	0.071	-46	112	110	11	09:29-10:55	
2022 Oct 04	09:26	-14:12	73	-26	0.071	-45	119	110	11	09:26-11:16	
2022 Oct 05	09:24	-14:28	76	-25	0.071	-44	127	120	11	09:24-11:36	
2022 Oct 06	09:21	-14:44	78	-23	0.072	-43	135	120	11	09:21-11:54	
2022 Oct 07	09:18	-14:59	81	-22	0.072	-41	141	120	11	09:18-12:11	
2022 Oct 08	09:16	-15:13	83	-21	0.072	-40	147	120	11	09:16-12:26	
2022 Oct 09	09:14	-15:26	86	-19	0.073	-38	152	120	10	09:14-12:41	
2022 Oct 10	09:11	-15:38	88	-18	0.074	-37	156	120	10	09:11-12:55	
2022 Oct 11	09:09	-15:50	90	-16	0.075	-35	160	110	10	09:09-13:07	
2022 Oct 12	09:07	-16:00	92	-15	0.076	-33	162	110	9	09:07-13:19	
2022 Oct 13	09:05	-16:10	94	-13	0.077	-32	165	100	9	09:05-13:30	
2022 Oct 14	09:02	-16:19	96	-12	0.078	-30	166	99	8	09:02-13:40	
2022 Oct 15	09:00	-16:27	98	-11	0.080	-29	168	93	8	09:00-13:49	
2022 Oct 16	08:58	-16:35	99	-9	0.081	-27	168	88	7	08:58-13:57	
2022 Oct 17	08:56	-16:42	101	-8	0.083	-26	168	82	7	08:56-14:05	
2022 Oct 18	08:53	-16:48	103	-7	0.085	-24	168	77	6	08:53-14:12	
2022 Oct 19	08:51	-16:54	104	-6	0.086	-23	168	72	6	08:51-14:19	
2022 Oct 20	08:49	-17:00	105	-5	0.088	-22	167	67	6	08:49-14:25	
2022 Oct 21	08:46	-17:04	107	-4	0.090	-20	166	62	5	08:46-14:30	

# Goldstone Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (2/2)

start date	Start	Stop	Monostatic								
			UTC			SNR/			SNR/ GSSR/GBT		
			RA	dec	dist	lat	runs	day	run	Overlap	
			(degrees)	(au)	(deg)						
2022 Oct 22	08:44-17:09	108	-3	0.092	-19	165	57	5	08:44-14:35		
2022 Oct 23	08:41-17:13	109	-2	0.094	-18	164	53	5	08:41-14:39		
2022 Oct 24	08:38-17:16	110	-1	0.095	-17	163	49	4	08:38-14:43		
2022 Oct 25	08:36-17:19	111	0	0.097	-16	161	46	4	08:36-14:47		
2022 Oct 26	08:33-17:22	112	+1	0.099	-15	159	42	4	08:33-14:50		
2022 Oct 27	08:30-17:25	113	+2	0.102	-14	158	39	3	08:30-14:53		
2022 Oct 28	08:28-17:27	114	+3	0.104	-13	156	36	3	08:28-14:55		
2022 Oct 29	08:25-17:29	115	+4	0.106	-12	154	34	3	08:25-14:57		
2022 Oct 30	08:22-17:30	116	+5	0.108	-11	153	31	3	08:22-14:59		
2022 Oct 31	08:19-17:31	116	+5	0.110	-10	151	29	3	08:19-15:01		
2022 Nov 01	08:16-17:32	117	+6	0.112	-9	149	27	2			
2022 Nov 02	08:13-17:33	118	+7	0.114	-8	147	25	2			
2022 Nov 03	08:09-17:34	119	+7	0.116	-7	146	23	2			
2022 Nov 04	08:06-17:34	119	+8	0.118	-7	144	22	2			
2022 Nov 05	08:03-17:34	120	+9	0.121	-6	142	20	2			
2022 Nov 06	08:00-17:34	120	+9	0.123	-5	141	19	2			
2022 Nov 07	07:56-17:34	121	+10	0.125	-4	139	18	2			
2022 Nov 08	07:53-17:34	121	+10	0.127	-4	137	17	2			
2022 Nov 09	07:49-17:33	122	+11	0.129	-3	136	16	1			
2022 Nov 10	07:46-17:33	122	+11	0.131	-3	134	15	1			
2022 Nov 11	07:42-17:32	123	+12	0.133	-2	133	14	1			
2022 Nov 12	07:38-17:31	123	+12	0.135	-1	131	13	1			
2022 Nov 13	07:34-17:30	124	+13	0.138	-1	130	12	1			
2022 Nov 14	07:31-17:28	124	+13	0.140	0	128	12	1			
2022 Nov 15	07:27-17:27	124	+14	0.142	0	127	11	1			
2022 Nov 16	07:23-17:25	124	+14	0.144	+1	126	10	1			
2022 Nov 17	07:19-17:24	125	+15	0.146	+1	124	10	1			
2022 Nov 18	07:15-17:22	125	+15	0.148	+2	123	9	1			

# Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (1/3)

UTC	start date	Start	Stop			SNR/		SNR/	
				RA	dec	dist	lat	runs	day
				(degrees)	(au)	(deg)			run
2022 Oct 24	09:16-09:57	110	-1	0.095	-17	12	230	68	
2022 Oct 25	09:05-10:08	111	0	0.097	-16	19	291	71	
2022 Oct 26	08:58-10:16	112	+1	0.099	-15	23	319	72	
2022 Oct 27	08:52-10:21	113	+2	0.101	-14	26	335	72	
2022 Oct 28	08:47-10:26	114	+3	0.103	-13	28	341	72	
2022 Oct 29	08:42-10:29	115	+4	0.105	-12	30	342	70	
2022 Oct 30	08:38-10:32	116	+4	0.107	-11	31	332	65	
2022 Oct 31	08:34-10:34	116	+5	0.110	-10	32	319	61	
2022 Nov 01	08:31-10:36	117	+6	0.112	-9	33	304	57	
2022 Nov 02	08:27-10:37	118	+7	0.114	-8	34	290	53	
2022 Nov 03	08:24-10:38	118	+7	0.116	-7	34	273	50	
2022 Nov 04	08:21-10:38	119	+8	0.118	-7	35	259	46	
2022 Nov 05	08:18-10:38	120	+9	0.120	-6	35	245	44	
2022 Nov 06	08:15-10:38	120	+9	0.122	-5	35	231	41	
2022 Nov 07	08:12-10:38	121	+10	0.125	-5	35	218	39	
2022 Nov 08	08:08-10:37	121	+10	0.127	-4	35	205	36	
2022 Nov 09	08:05-10:36	122	+11	0.129	-3	35	194	34	
2022 Nov 10	08:02-10:35	122	+11	0.131	-3	35	183	32	
2022 Nov 11	07:59-10:33	123	+12	0.133	-2	35	173	31	
2022 Nov 12	07:56-10:32	123	+12	0.135	-1	34	162	29	
2022 Nov 13	07:53-10:30	123	+13	0.137	-1	34	154	27	
2022 Nov 14	07:50-10:28	124	+13	0.139	0	34	146	26	
2022 Nov 15	07:47-10:26	124	+14	0.141	0	34	138	25	
2022 Nov 16	07:43-10:24	124	+14	0.144	+1	33	130	23	

# Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (2/3)

UTC start date	Start	Stop	RA	dec	SNR/ SNR/		day	run
					dist (degrees)	lat (au)		
2022 Nov 17	07:40-10:22	125 +15	0.146	+1	33	124	22	
2022 Nov 18	07:37-10:19	125 +15	0.148	+2	33	117	21	
2022 Nov 19	07:33-10:16	125 +16	0.150	+2	32	111	20	
2022 Nov 20	07:30-10:14	125 +16	0.152	+3	32	105	19	
2022 Nov 21	07:26-10:11	126 +17	0.154	+3	32	100	18	
2022 Nov 22	07:23-10:07	126 +17	0.156	+4	31	95	18	
2022 Nov 23	07:19-10:04	126 +17	0.158	+4	30	89	17	
2022 Nov 24	07:15-10:01	126 +18	0.160	+5	28	82	16	
2022 Nov 25	07:12-09:57	126 +18	0.162	+5	28	78	15	
2022 Nov 26	07:08-09:54	126 +19	0.164	+5	28	75	15	
2022 Nov 27	07:04-09:50	126 +19	0.166	+6	28	72	14	
2022 Nov 28	07:00-09:46	126 +19	0.168	+6	29	71	14	
2022 Nov 29	06:56-09:42	126 +20	0.170	+6	29	67	13	
2022 Nov 30	06:52-09:38	126 +20	0.172	+7	29	64	12	
2022 Dec 01	06:48-09:34	126 +21	0.174	+7	28	61	12	
2022 Dec 02	06:44-09:29	126 +21	0.176	+8	28	58	11	
2022 Dec 03	06:40-09:25	126 +21	0.179	+8	27	55	11	
2022 Dec 04	06:36-09:20	126 +22	0.181	+8	27	53	11	
2022 Dec 05	06:31-09:16	126 +22	0.183	+9	27	50	10	
2022 Dec 06	06:27-09:11	125 +22	0.185	+9	26	48	10	
2022 Dec 07	06:22-09:06	125 +23	0.187	+9	26	46	9	
2022 Dec 08	06:18-09:01	125 +23	0.190	+9	25	43	9	
2022 Dec 09	06:13-08:56	125 +23	0.192	+10	25	41	9	
2022 Dec 10	06:09-08:51	125 +24	0.194	+10	25	39	8	

# Arecibo Signal-to-Noise Ratios for the Primary during the 2022 radar apparition (3/3)

UTC	start date	Start	Stop			SNR/		dist	lat	runs	day	run
				RA	dec	(degrees)	(au)	(deg)				
2022	Dec 11	06:04-08:46	124	+24	0.197	+10	24	37	8			
2022	Dec 12	06:00-08:40	124	+24	0.199	+10	24	35	8			
2022	Dec 13	05:55-08:35	124	+25	0.202	+11	23	33	7			
2022	Dec 14	05:50-08:29	123	+25	0.204	+11	23	32	7			
2022	Dec 15	05:45-08:24	123	+25	0.207	+11	23	30	7			
2022	Dec 16	05:40-08:18	123	+26	0.210	+11	22	28	6			
2022	Dec 17	05:36-08:12	122	+26	0.212	+12	22	27	6			
2022	Dec 18	05:31-08:06	122	+26	0.215	+12	21	25	6			
2022	Dec 19	05:26-08:00	122	+27	0.218	+12	21	24	5			
2022	Dec 20	05:21-07:54	121	+27	0.221	+12	21	23	5			
2022	Dec 21	05:16-07:49	121	+27	0.224	+12	20	21	5			
2022	Dec 22	05:11-07:42	121	+27	0.227	+13	20	20	5			
2022	Dec 23	05:06-07:36	120	+28	0.230	+13	19	19	5			
2022	Dec 24	05:00-07:30	120	+28	0.234	+13	19	18	4			
2022	Dec 25	04:55-07:24	119	+28	0.237	+13	19	17	4			
2022	Dec 26	04:50-07:18	119	+28	0.241	+13	18	16	4			
2022	Dec 27	04:45-07:12	118	+28	0.244	+13	18	15	4			
2022	Dec 28	04:40-07:06	118	+29	0.248	+13	17	14	3			
2022	Dec 29	04:35-07:00	118	+29	0.252	+13	17	13	3			
2022	Dec 30	04:29-06:54	117	+29	0.256	+14	17	12	3			
2022	Dec 31	04:24-06:48	117	+29	0.260	+14	16	11	3			
2023	Jan 01	04:19-06:41	116	+29	0.264	+14	16	11	3			
2023	Jan 02	04:14-06:35	116	+30	0.269	+14	15	10	3			
2023	Jan 03	04:08-06:29	115	+30	0.273	+14	15	9	3			
2023	Jan 04	04:03-06:23	115	+30	0.278	+14	15	9	2			

# Goldstone Signal-to-Noise Ratios for the Secondary during the 2022 radar apparition

	UTC							SNR/	
start date	Start	Stop	RA dec	dist	lat	runs	day	SNR/	
2022 Sep 25	10:07-11:08		47 -34	0.078	-50	23	6	1	
2022 Sep 26	09:58-11:33		50 -34	0.076	-50	37	9	1	
2022 Sep 27	09:52-11:56		53 -33	0.075	-50	49	11	2	
2022 Sep 28	09:47-12:17		56 -32	0.074	-50	60	12	2	
2022 Sep 29	09:43-12:38		59 -32	0.073	-49	71	14	2	
2022 Sep 30	09:39-12:58		62 -31	0.072	-49	82	16	2	
2022 Oct 01	09:35-13:17		65 -30	0.072	-48	92	18	2	
2022 Oct 02	09:32-13:36		67 -28	0.072	-47	102	19	2	
2022 Oct 03	09:29-13:54		70 -27	0.071	-46	111	20	2	
2022 Oct 04	09:26-14:12		73 -26	0.071	-45	119	21	2	
2022 Oct 05	09:24-14:28		76 -25	0.071	-44	127	22	2	
2022 Oct 06	09:21-14:44		78 -23	0.072	-43	135	23	2	
2022 Oct 07	09:18-14:59		81 -22	0.072	-41	141	23	2	
2022 Oct 08	09:16-15:13		83 -21	0.072	-40	147	23	2	
2022 Oct 09	09:14-15:26		86 -19	0.073	-38	152	23	2	
2022 Oct 10	09:11-15:38		88 -18	0.074	-37	156	22	2	
2022 Oct 11	09:09-15:50		90 -16	0.075	-35	160	21	2	
2022 Oct 12	09:07-16:00		92 -15	0.076	-33	162	21	2	
2022 Oct 13	09:05-16:10		94 -13	0.077	-32	165	20	2	
2022 Oct 14	09:02-16:19		96 -12	0.078	-30	166	19	2	
2022 Oct 15	09:00-16:27		98 -11	0.080	-29	168	18	2	
2022 Oct 16	08:58-16:35		99 -9	0.081	-27	168	17	1	
2022 Oct 17	08:56-16:42		101 -8	0.083	-26	168	16	1	
2022 Oct 18	08:53-16:48		103 -7	0.085	-24	168	15	1	
2022 Oct 19	08:51-16:54		104 -6	0.086	-23	168	14	1	
2022 Oct 20	08:49-17:00		105 -5	0.088	-22	167	13	1	
2022 Oct 21	08:46-17:04		107 -4	0.090	-20	166	12	1	
2022 Oct 22	08:44-17:09		108 -3	0.092	-19	165	11	1	
2022 Oct 23	08:41-17:13		109 -2	0.094	-18	164	10	1	
2022 Oct 24	08:38-17:16		110 -1	0.095	-17	163	9	1	

# Arecibo Signal-to-Noise Ratios for the Secondary during the 2022 radar apparition (1/2)

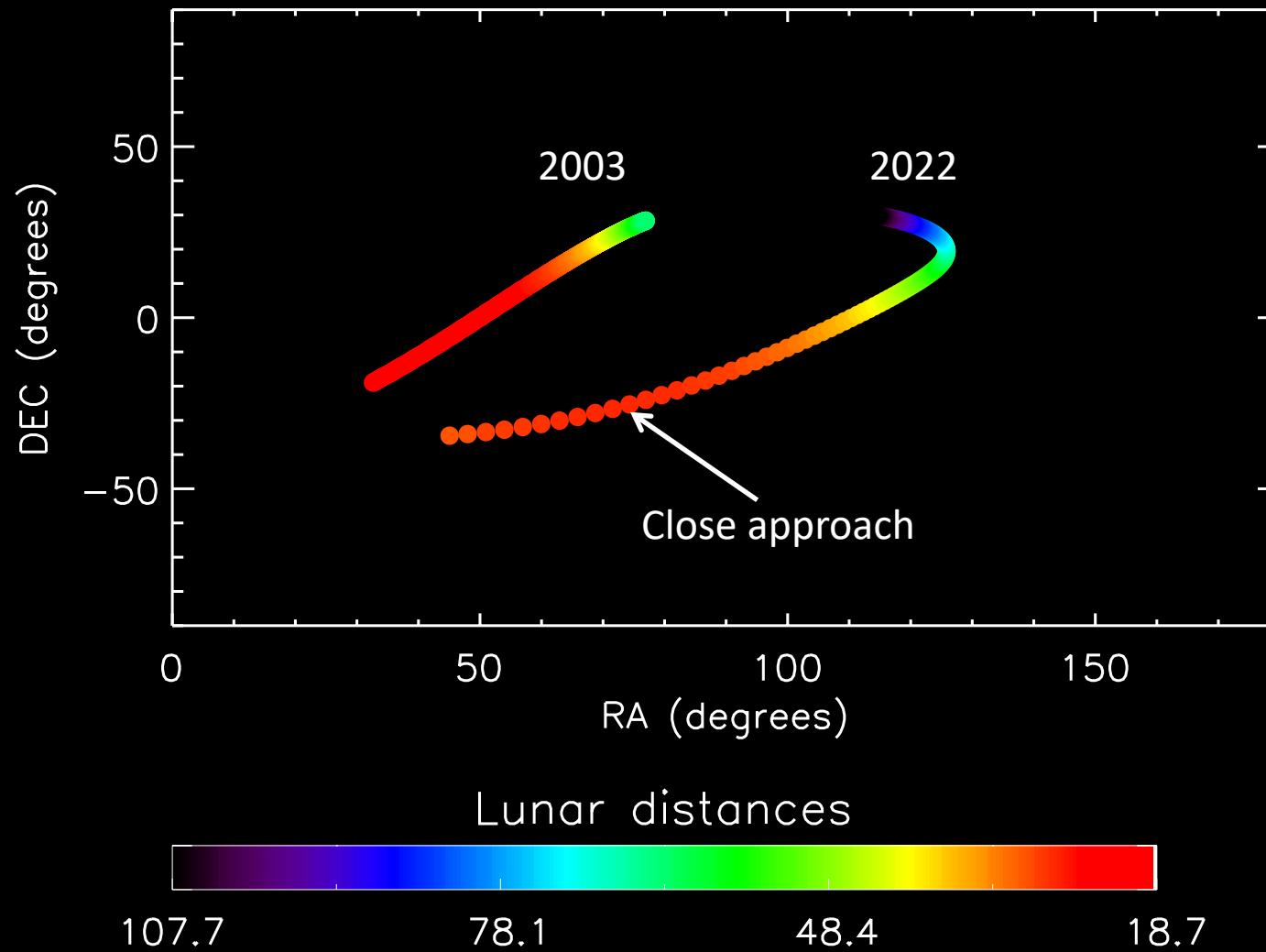
start	date	UTC			dist	lat	runs	SNR/	
		Start	Stop	RA dec				day	run
2022	Oct 24	09:16	-09:57	110	-1	0.095	-17	12	44
2022	Oct 25	09:05	-10:08	111	0	0.097	-16	19	55
2022	Oct 26	08:58	-10:16	112	+1	0.099	-15	23	61
2022	Oct 27	08:52	-10:21	113	+2	0.101	-14	26	64
2022	Oct 28	08:47	-10:26	114	+3	0.103	-13	28	65
2022	Oct 29	08:42	-10:29	115	+4	0.105	-12	30	65
2022	Oct 30	08:38	-10:32	116	+4	0.107	-11	31	63
2022	Oct 31	08:34	-10:34	116	+5	0.110	-10	32	60
2022	Nov 01	08:31	-10:36	117	+6	0.112	-9	33	58
2022	Nov 02	08:27	-10:37	118	+7	0.114	-8	34	55
2022	Nov 03	08:24	-10:38	118	+7	0.116	-7	34	52
2022	Nov 04	08:21	-10:38	119	+8	0.118	-7	35	49
2022	Nov 05	08:18	-10:38	120	+9	0.120	-6	35	46
2022	Nov 06	08:15	-10:38	120	+9	0.122	-5	35	44
2022	Nov 07	08:12	-10:38	121	+10	0.125	-5	35	41
2022	Nov 08	08:08	-10:37	121	+10	0.127	-4	35	39
2022	Nov 09	08:05	-10:36	122	+11	0.129	-3	35	37
2022	Nov 10	08:02	-10:35	122	+11	0.131	-3	35	35
2022	Nov 11	07:59	-10:33	123	+12	0.133	-2	35	33
2022	Nov 12	07:56	-10:32	123	+12	0.135	-1	34	31
2022	Nov 13	07:53	-10:30	123	+13	0.137	-1	34	29
2022	Nov 14	07:50	-10:28	124	+13	0.139	0	34	28
2022	Nov 15	07:47	-10:26	124	+14	0.141	0	34	26

# Arecibo Signal-to-Noise Ratios for the Secondary during the 2022 radar apparition

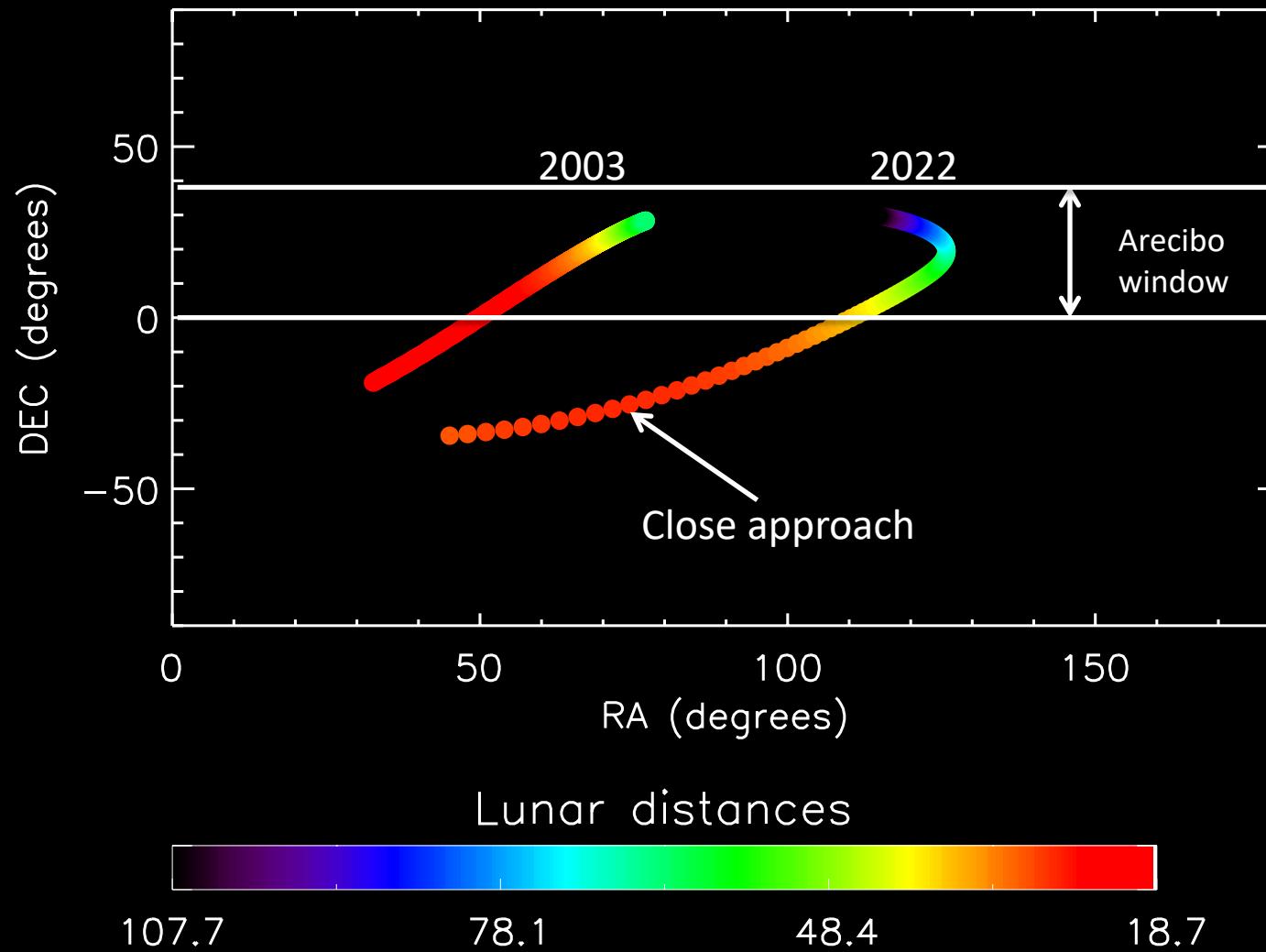
(2/2)

	UTC						SNR/	SNR/		
start	date	Start	Stop	RA	dec	dist	lat	runs	day	run
2022	Nov 16	07:43-10:24	124 +14	0.144	+1	33	25	4		
2022	Nov 17	07:40-10:22	125 +15	0.146	+1	33	23	4		
2022	Nov 18	07:37-10:19	125 +15	0.148	+2	33	22	4		
2022	Nov 19	07:33-10:16	125 +16	0.150	+2	32	21	4		
2022	Nov 20	07:30-10:14	125 +16	0.152	+3	32	20	4		
2022	Nov 21	07:26-10:11	126 +17	0.154	+3	32	19	3		
2022	Nov 22	07:23-10:07	126 +17	0.156	+4	31	18	3		
2022	Nov 23	07:19-10:04	126 +17	0.158	+4	30	17	3		
2022	Nov 24	07:15-10:01	126 +18	0.160	+5	28	16	3		
2022	Nov 25	07:12-09:57	126 +18	0.162	+5	28	15	3		
2022	Nov 26	07:08-09:54	126 +19	0.164	+5	28	14	3		
2022	Nov 27	07:04-09:50	126 +19	0.166	+6	28	14	3		
2022	Nov 28	07:00-09:46	126 +19	0.168	+6	29	13	3		
2022	Nov 29	06:56-09:42	126 +20	0.170	+6	29	13	2		
2022	Nov 30	06:52-09:38	126 +20	0.172	+7	29	12	2		
2022	Dec 01	06:48-09:34	126 +21	0.174	+7	28	12	2		
2022	Dec 02	06:44-09:29	126 +21	0.176	+8	28	11	2		
2022	Dec 03	06:40-09:25	126 +21	0.179	+8	27	10	2		
2022	Dec 04	06:36-09:20	126 +22	0.181	+8	27	10	2		
2022	Dec 05	06:31-09:16	126 +22	0.183	+9	27	10	2		
2022	Dec 06	06:27-09:11	125 +22	0.185	+9	26	9	2		

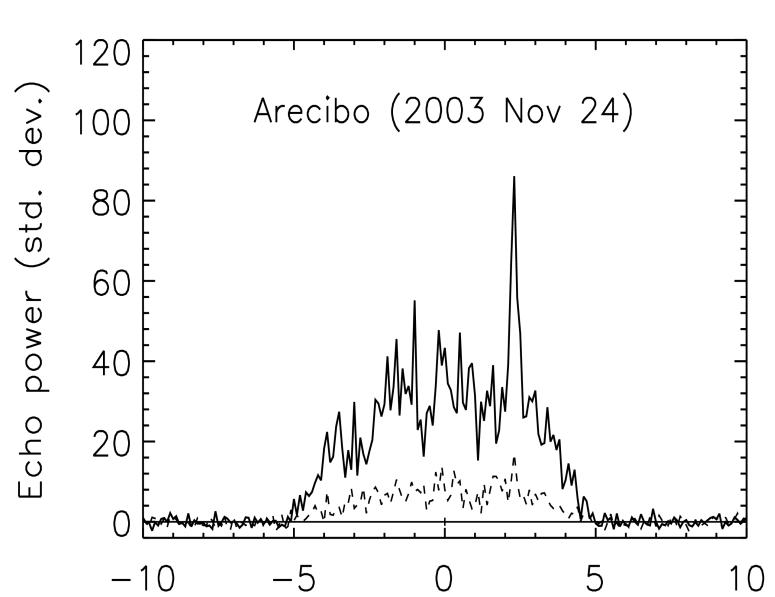
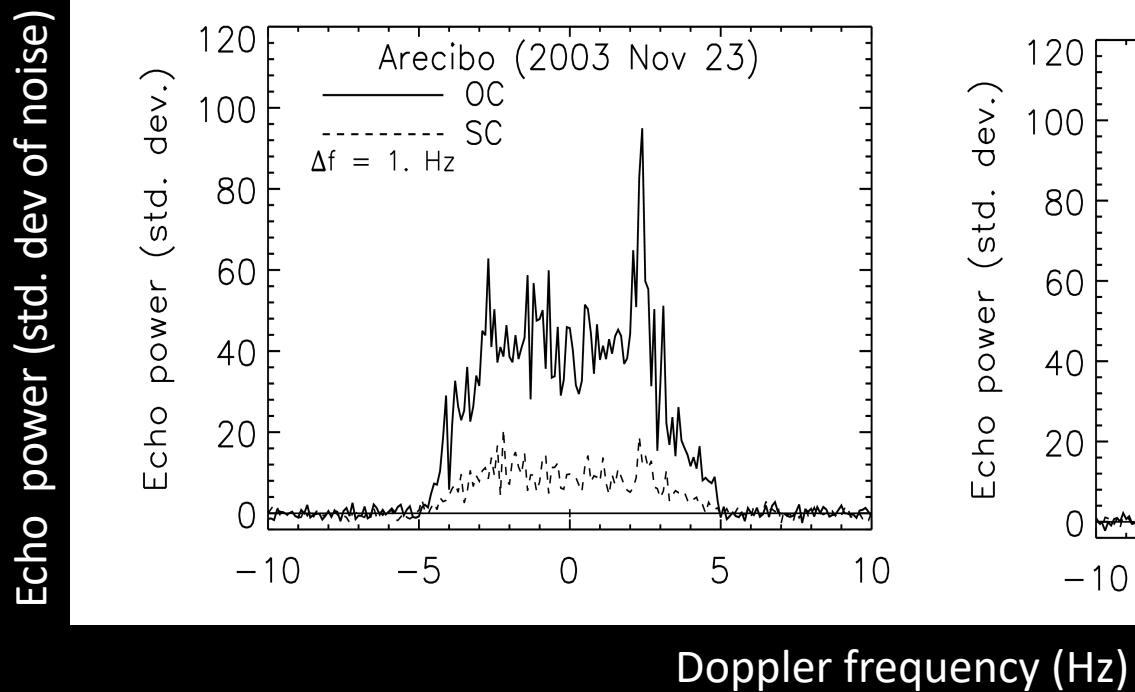
# Observing geometry in 2022



# Observing geometry in 2022



# Arecibo echo power spectra from 2003

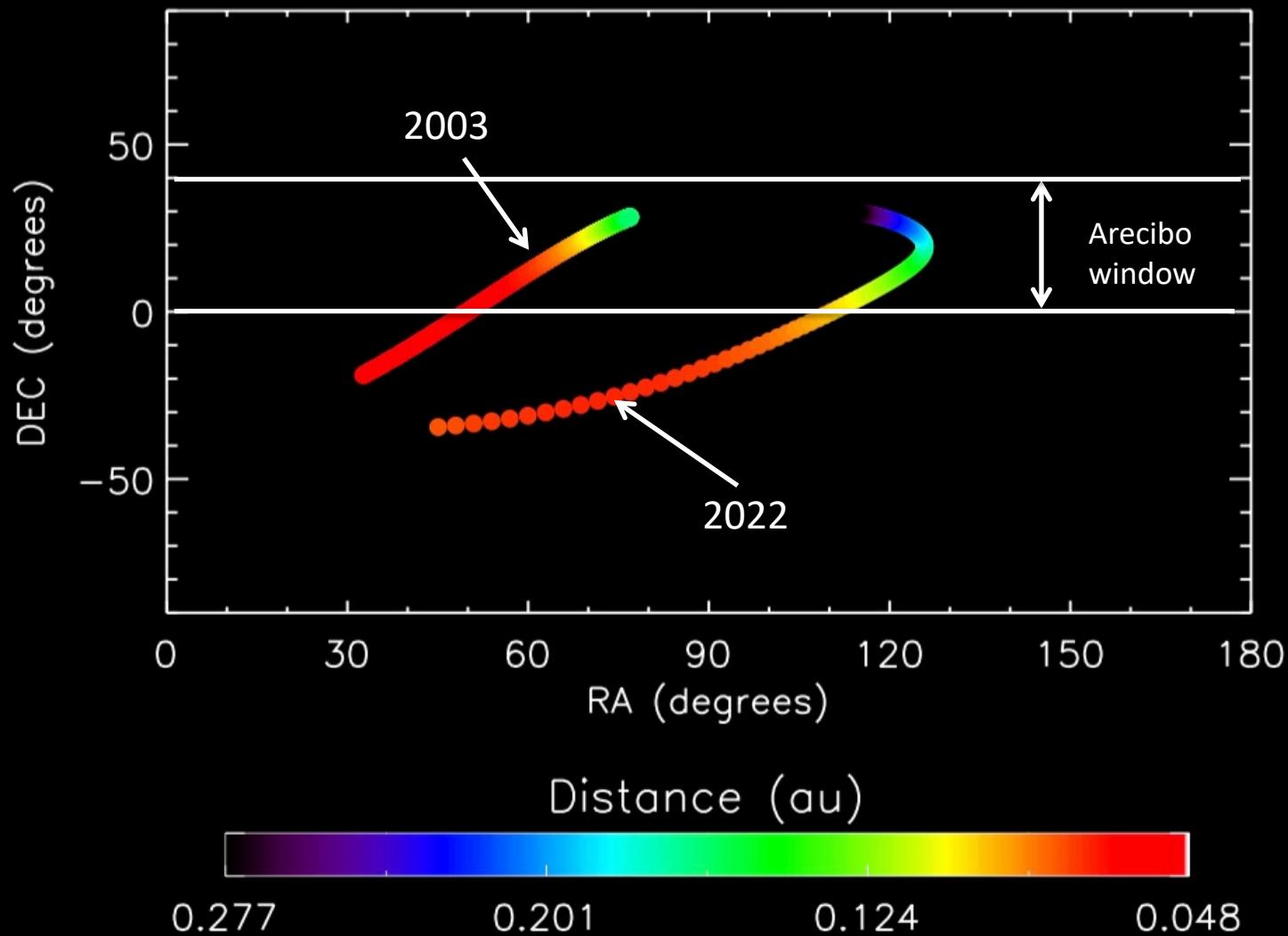


The strongest Arecibo SNRs in 2022 will be 1/6th of those shown here

# Radar opportunity in 2022

- Earth close approach on October 4
  - Encounter distance will be 0.071 au (1.5 x the 2003 close approach)
- Goldstone target: Sep 25 – Nov 18
  - Maximum SNR 1/4<sup>th</sup> as strong as 2003
- Arecibo target from Oct 24 – Jan 04
  - Maximum SNR 1/3<sup>rd</sup> as strong as 2003

# Observing geometry in 2022



# Goldstone primary SNRs

UTC start date	RA, dec	dist	lat	SNR/ day	SNR/ run
2022 Sep 25	47, -34	0.078	-50	33	7
:					
2022 Oct 03	70, -27	0.071	-46	110	11
2022 Oct 04	73, -26	0.071	-45	110	11
2022 Oct 05	76, -25	0.071	-44	120	11
2022 Oct 06	78, -23	0.072	-43	120	11
2022 Oct 07	81, -22	0.072	-41	120	11
2022 Oct 08	83, -21	0.072	-40	120	11
:					
2022 Nov 18	125, 15	0.148	+2	9	1

Secondary SNRs will be 1/6th of the primary SNRs

# Arecibo primary SNRs

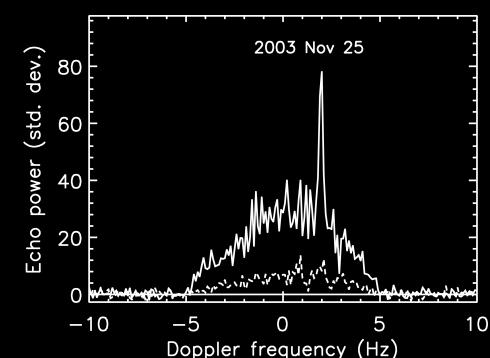
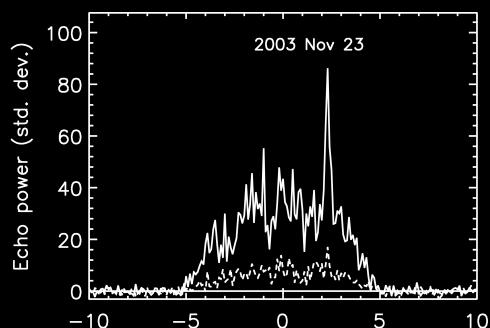
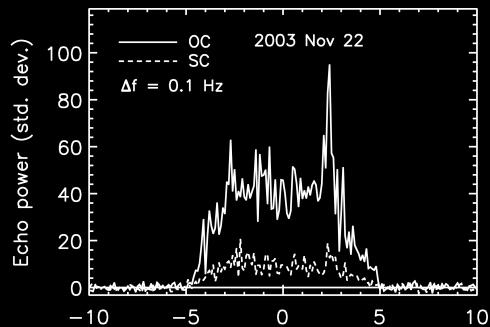
UTC start date	RA, dec	dist	lat	SNR/ day	SNR/ run
2022 Oct 25	111, 0	0.097	-16	291	71
2022 Oct 26	112, +1	0.099	-15	319	72
2022 Oct 27	113, +2	0.101	-14	335	72
2022 Oct 28	114, +3	0.103	-13	341	72
2022 Oct 29	115, +4	0.105	-12	342	70
2022 Oct 30	116, +4	0.107	-11	332	65
2022 Oct 31	116, +5	0.110	-10	319	61
2022 Nov 01	117, +6	0.112	-9	304	57
2022 Nov 02	118, +7	0.114	-8	290	53
2022 Nov 03	118, +7	0.116	-7	273	50
2022 Nov 04	119, +8	0.118	-7	259	46
2022 Nov 05	120, +9	0.120	-6	245	44
:					
2023 Jan 04	115, +30	0.278	+14	9	2

# Radar opportunity in 2022

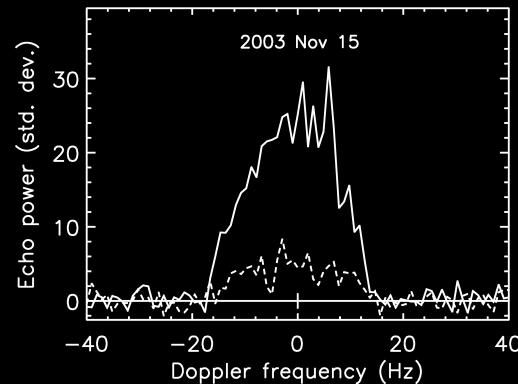
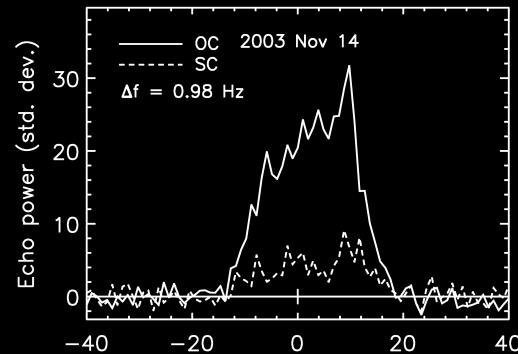
- Resolutions: 2x coarser than those in 2003
  - Goldstone: 150 m/pixel
  - Arecibo: 30 m/pixel
- Using GBT to receive Goldstone signals will improve resolution to 75 m/pixel

# Echo power spectra

Arecibo



Goldstone



S-band (Arecibo):

OC albedo =  $0.20 \pm 25\%$

SC/OC =  $0.22 \pm 20\%$

X-band (Goldstone):

OC albedo =  $0.30 \pm 35\%$

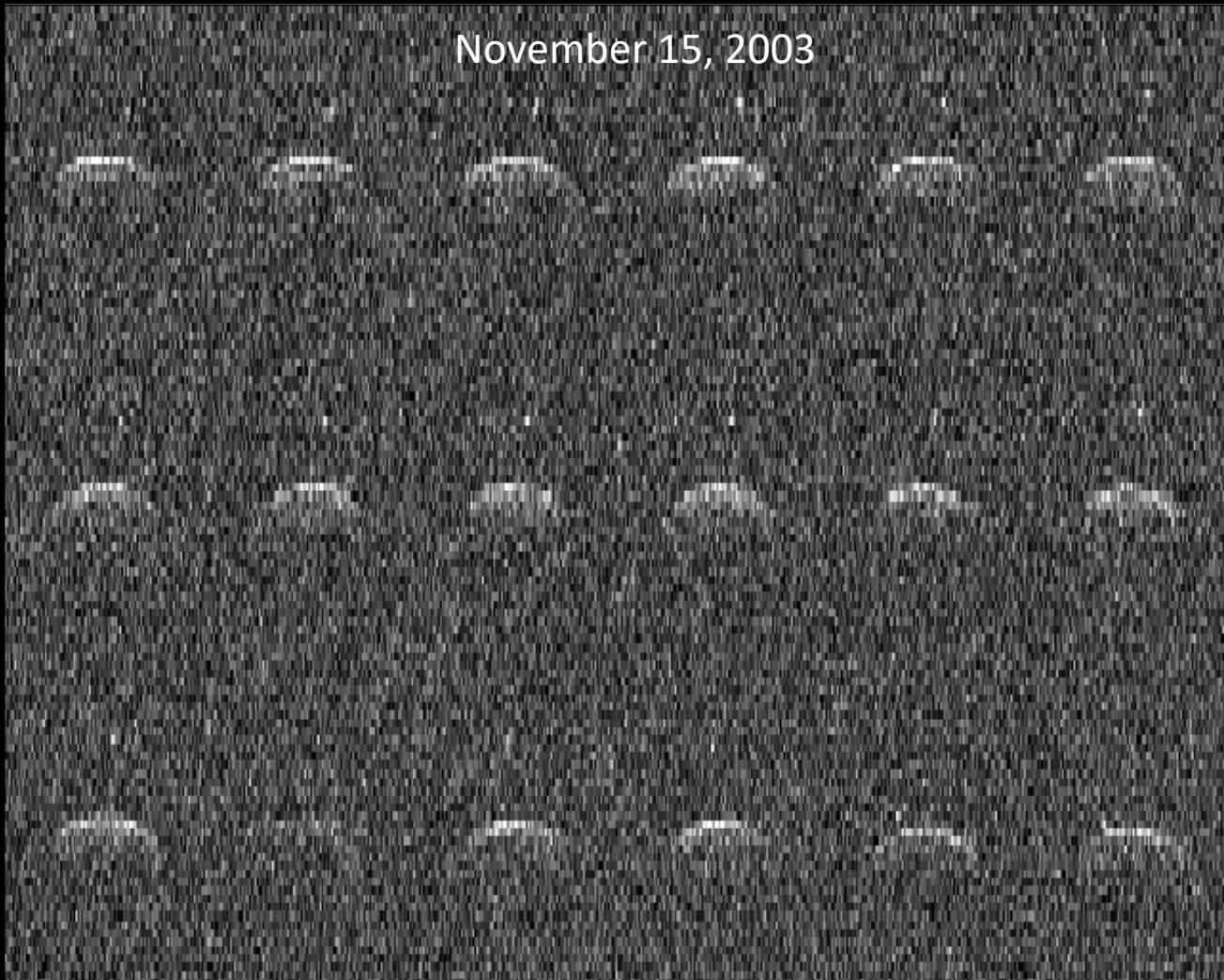
SC/OC =  $0.20 \pm 30\%$

=> Surface/near-surface density =  $1000 \text{ kg/m}^3$

# Goldstone images

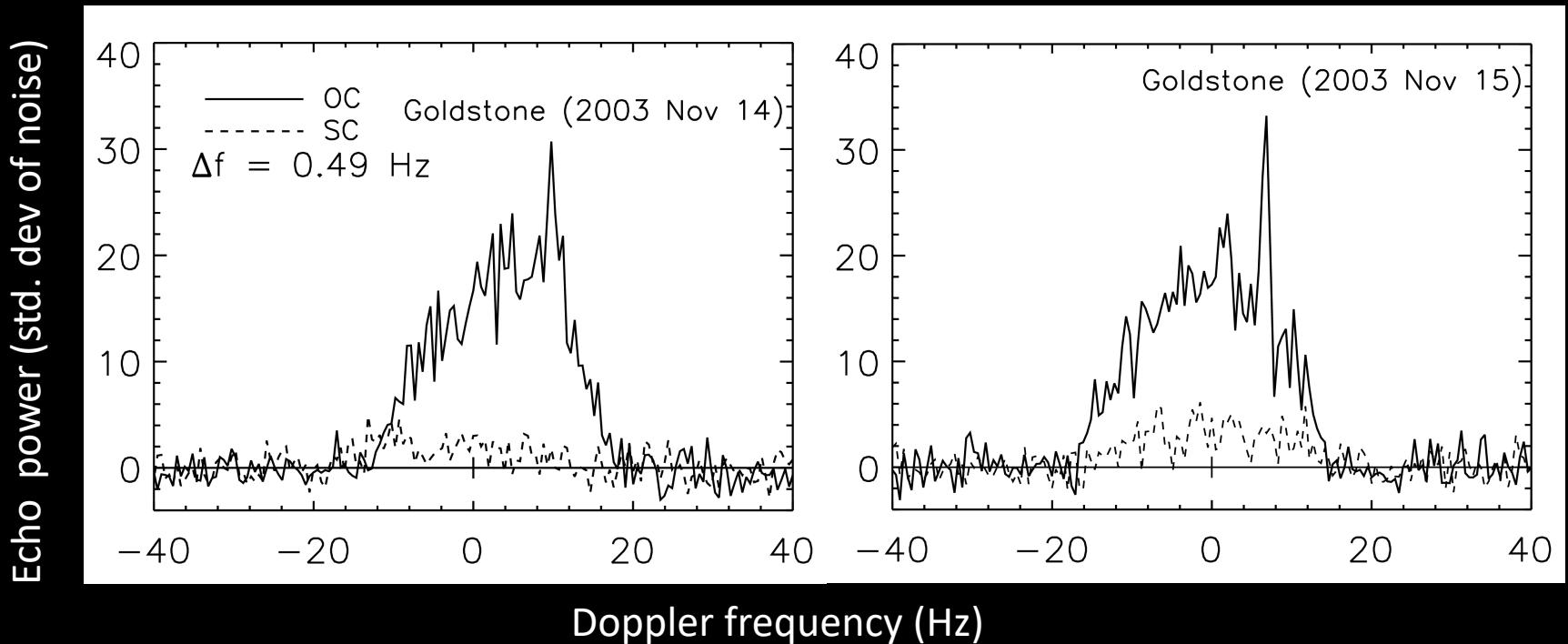
November 15, 2003

Range (75 m/pixel) →



Doppler Frequency (0.5 Hz/pixel) →

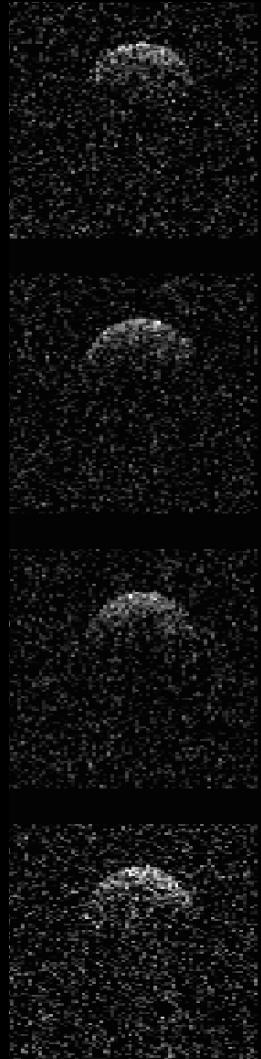
# Goldstone echo power spectra from 2003



The highest Arecibo SNRs in 2022 will be 1.6x stronger than in these images.  
The highest Goldstone to Green Bank SNRs will be about half of these.

# Selected radar fits

Arecibo  
Nov 23

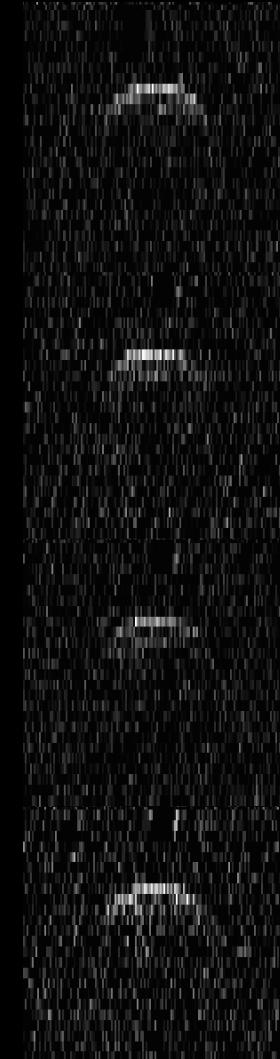


Data

Fit

Model

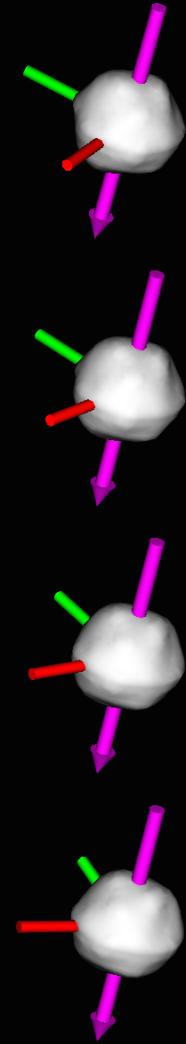
Goldstone  
Nov 15



Data

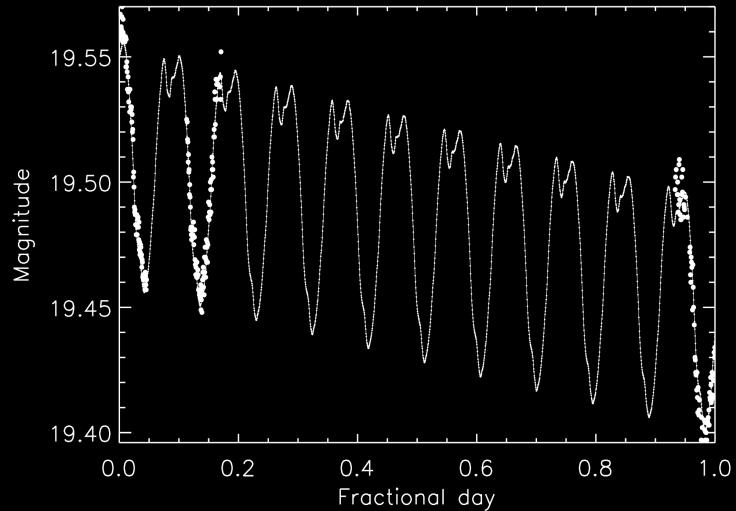
Fit

Model

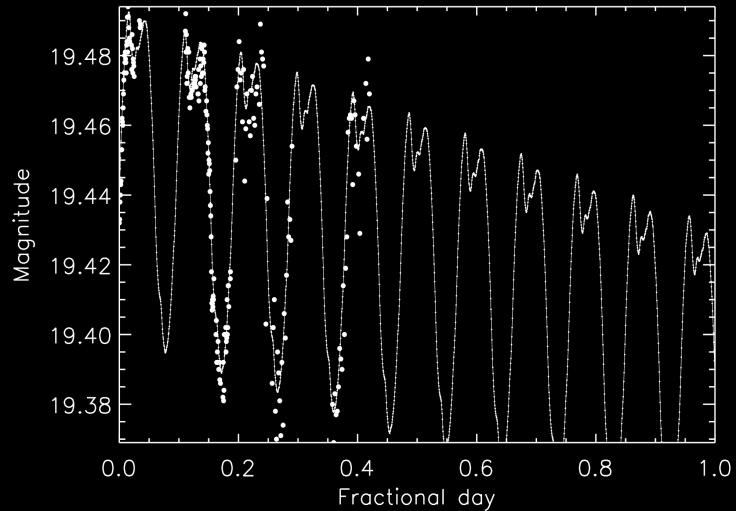


# Lightcurve fits (2003)

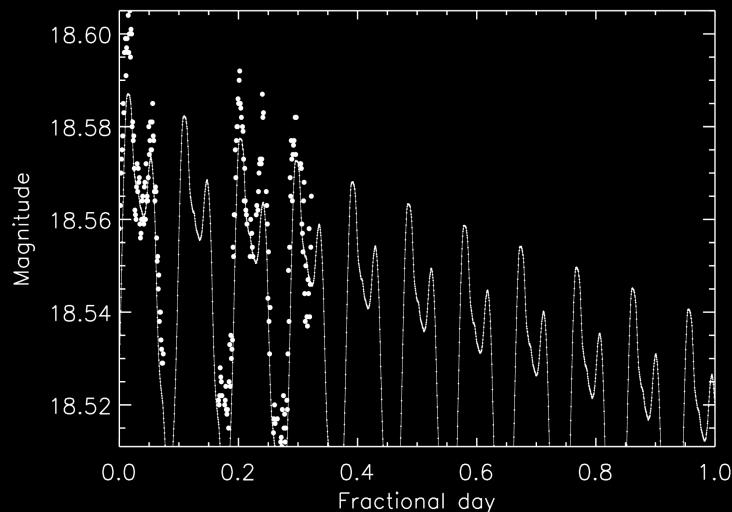
Nov 20



Nov 21



Nov 29



Dec 18

